Estimation of long-term throughput degradation of GOES 8 & 9 visible channels by statistical analysis of star measurements

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ABSTRACT

Each Imager and Sounder on the present generation of GOES satellites has an eight-channel visible detector array. These visible arrays perform star-sensing measurements to establish inertial attitude references so that earth observations can be registered to the earth's latitude and longitude coordinates. The Imager's visible array also performs earth observations. We have used the archived signal levels of star measurements to estimate the long-term throughput loss in these channels of the Imager and Sounder on GOES 8 and GOES 9. An exponential decay rate was determined for each sensor by averaging the values derived from each of approximately 30 stars over a time interval of at least 500 days. Large degradations in image quality occur during local night, when direct sunlight enters the optical ports of the two sensors. Therefore, we have deleted observations made during the 10 hour interval around midnight, satellite time, from our analysis. Variable stars and stars with low signal-to-noise ratios were also excluded. The annual throughput losses for the four sensors, derived from measured star signal levels, range from 3.8% to 9.6%.

Keywords: calibration, visible, GOES, stars, albedo

1. OVERVIEW

There are presently two operational GOES satellites in geostationary orbit. GOES 8, launched on April 13, 1994, is deployed at 75° W longitude (GOES East) and GOES 9, launched on May 23, 1995, is deployed at 135° W longitude (GOES-West). Each of these satellites has two independent sensors, an Imager and a Sounder, observing the earth in the visible and in multiple IR channels. At intervals of approximately 30 minutes, the earth-observing operations of each sensor are interrupted and the sensor transitions into its starsense mode. In this mode, the sensor is commanded to observe four pre-selected stars, preferably in the corners of its 23° by 21° field of regard. Differences between predicted and actual star positions are used to determine the spacecraft's attitude and to compensate for pointing errors due to thermal distortion of the scan mirror's gimbal system.

The GOES Imagers use the same visible detectors for earth imaging that they use for their starsense measurements. The GOES Sounders have starsense detectors that are dedicated to that function alone.

The GOES Imagers are well-suited to study long-term, climatic trends by measuring changes in albedo levels over periods of many years. In viewing the Western Hemisphere from geostationary orbit, the GOES 8 & 9 Imagers each provide a full-disk image, with near-hemispheric coverage, every three hours. Therefore, they are able to make diurnal cycle observations of processes that impact long-term global change. There is an excellent opportunity for cross-calibration among Imagers on different GOES satellites because each new satellite is tested in orbit before an old satellite is de-commissioned. In order to extract information on global change from the GOES Imager's data, however, it is highly beneficial to determine the long-term changes in the throughput of its visible channel.[1]

Long-term degradation of the throughput of either the Imager or the Sounder may also provide valuable diagnostic information about the cause of the degradation, particularly when correlated with the "housekeeping" data that includes temperature profiles of the scan mirror and other optical train elements.

The visible channels on the Imager and the Sounder were not designed to perform quantitative radiometry. Each sensor has a full aperture blackbody for on-orbit calibration of the gain of its thermal IR channels, but neither sensor has an on-board visible calibration mechanism. Any long-term changes in the throughput of the visible channel must be inferred from indirect measurements. To be most effective, any visible calibration technique must use a stable, well-characterized source that uniformly illuminates the entire aperture of the sensor.[2]

The starsense measurements provide a full-aperture, end-to-end method for calibrating the long-term degradation of the visible channels. Since they are already being performed every 30 minutes, for attitude determination, this visible radiometric calibration procedure can be implemented by performing additional analysis on data that is already being collected. It does not require a dedicated radiometric calibration procedure that reduces the time available for earth observations.

2. STARSENSE MEASUREMENT PROCEDURE

Each Imager and Sounder performs star-sensing measurements with a linear array of 8 silicon detectors, each having a 28x28 μradian instantaneous fields of view (IFOV). The Imager's silicon array, referred to as Band 1, is also used to observe the earth during the daytime. Its bandpass is 0.55-0.75 μm on GOES 8&9. (Band 1 on the GOES N-Q Imagers will have a bandpass of 0.52-0.72 μm.) The Sounder has an array with the same geometry that is used exclusively for star-sensing measurements. Its spectral response is basically that of silicon with a spectral notch produced by a beamsplitter. Thus, the starsense channels of the Imager and the Sounder have different spectral responses, as shown in Figure 1. Because of its greater response to near IR radiation, the Sounder's signal-to-noise ratio in the starsense mode exceeds that of the Imager, particularly in response to red stars.

The long axis of the 1x8 array has an orientation that is nominally north/south at the equator. The array elements are designated from V1 at the northern end through V8 at the southern end. The axis of this array rotates at a one-to-one ratio with the declination angle, δ. At positive declination angles, the Imager's axis points from north by $|\delta|$ east to south by $|\delta|$ west and the Sounder's axis points from north by $|\delta|$ west to south by $|\delta|$ east. The direction of image rotation is reversed for negative declination angles.

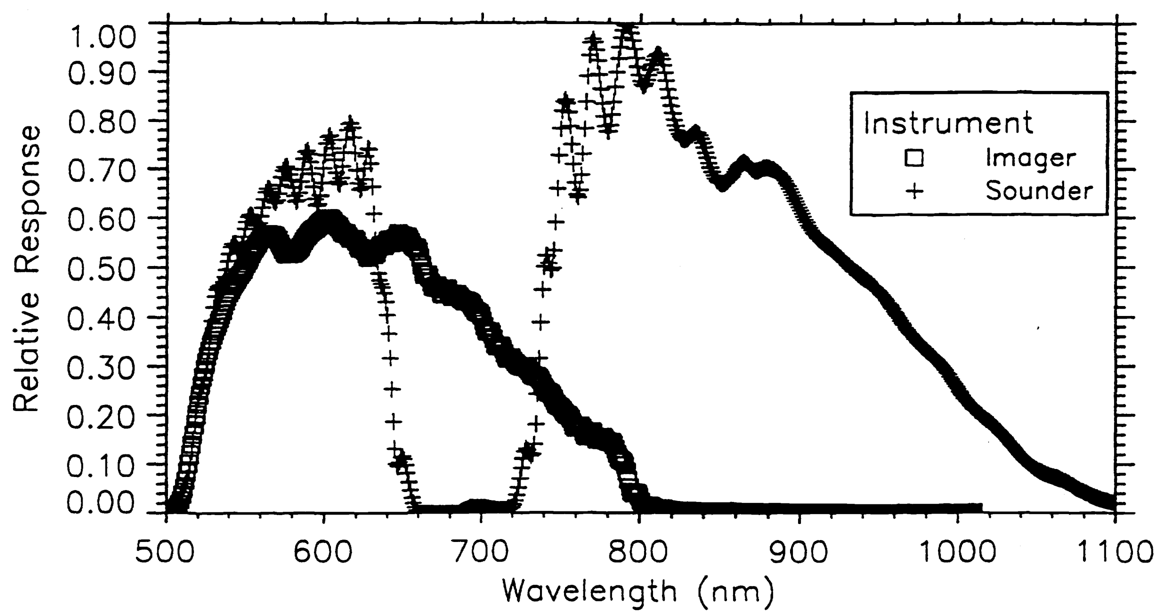

Figure 1. Spectral response of the GOES Imager and Sounder starsense channels

Each sensor interrupts its data-taking every 30 minutes to obtain an attitude reference from the stars. The line-of-sight (LOS) is commanded to observe four pre-selected stars, preferably in the corners of the sensor's 23° by 21° field of regard (FOR). The LOS is commanded to point slightly to the east of the anticipated position of each star. Since the satellite is stabilized in earth-referenced coordinates, it rotates once per sidereal day (23 hrs 56 min) with respect to the star field. Stars pass through the detector array from west to east at an angular velocity, ω(star) of:

$$\omega(\text{star}) = (72.9\ \mu\text{radians/sec})\cos(\delta) \tag{1}$$

The starsense signal level in each detector is determined by averaging samples over an interval of 0.22 sec corresponding to that detector's maximum output, and then subtracting the average background level measured over the search interval. When a star is detected in multiple pixels, its position is determined by interpolation and its total signal level is determined by summing the signal levels from the individual pixels. Only the total signal level is retained in archived data.

Most of the starsense measurements use a "double window" sequence of two looks for each star. The LOS is first commanded to an attitude that is east and 3.75 pixels (105 μradians) north of the star anticipated position, held stationary during the anticipated transit of the star, then commanded to a second attitude that is farther to the east and 3.75 pixels south of the star's declination and held stationary again. This algorithm creates a search window that subtends 15.5 pixels (434 μradians) in the north/south direction, with a nominal overlap of 14 μradians. Differences between predicted and actual star positions are used to determine the spacecraft's attitude and to compensate for pointing errors due to thermal distortion. After major attitude disturbances such as thruster firings, many starsense measurements are performed, with larger windows, to re-acquire a precise knowledge of the spacecraft's attitude.[3]

Each of the GOES sensors has a FOR that covers the 17.4° diameter earth disk that is visible from geostationary orbit. The FOR extends 23° from east and west and 10.5° from north and south, centered about nadir. The FOR of each sensor extends well beyond the earth's disk so that it can detect stars. Stars with declinations between -10.5° and +10.5° lie within the FOR during a interval of about 94 minutes each day. Stars with declinations between -10.5° and -8.7° or between +8.7° and +10.5° are observable throughout this 94 minute interval; stars with declinations between -8.7° and +8.7° are eclipsed by the earth during part of this interval. Each star enters and leaves the FOR about 4 minutes earlier on each successive day. The local spacecraft time interval during which each star is visible on a given day depends upon its right ascension, and is the same for GOES 8 and GOES 9; the Greenwich Mean Time (GMT) of these two intervals differs by 4 hours.[4]

3. GOES THERMAL ENVIRONMENT

Direct solar radiation enters the optical port of each sensor during local night, from 1800 hrs until 0600 hrs in spacecraft local time, whenever the sun is not in eclipse. The Imager's scan mirror is illuminated by direct solar radiation from approximately 2000 hrs until 0230 hrs; the Sounder' s scan mirror is illuminated from about 2130 hrs until 0400 hrs. Other optical and structural surfaces are also illuminated during the local night, causing the instruments to operate at much higher temperatures during the night than during the day.

The scan mirror is the first element in the optical train, so it is the most highly exposed to direct solar radiation (including vacuum UV), contamination, and micro-meteoroids. These environmental problems are expected to produce long-term degradation of the scan mirror's reflectivity, lowering the throughput of the visible channel and also increasing the heat absorbed by the scan mirror. The thermal conductance from the scan mirror to the body of the spacecraft is weak, passing through ball bearings on both gimbal axes. Therefore, the scan mirror heats rapidly when it is illuminated by direct sunlight for a period of several hours around local midnight.[5]

The maximum daily temperatures of the GOES 8 Imager's scan mirror from May 30, 1994 to May 20, 1998 are plotted in Figure 2. The level of solar illumination is highly variable with time of year, reaching maxima four times a year, about 20 days before and after each equinox, when angle between the ecliptic and the geostationary orbital plane is about 9°. The temperature profile also shows a long-term trend to increase with time. Similar behavior is exhibited by the scan mirrors of the other three sensors. The rapid, non-uniform solar heating that occurs during local night tends to warp the scan mirror. The scan mirror distortion is less severe on GOES 9 than on GOES 8, due to improvements in the mirror's design and fabrication. The direct solar illumination of the mirror also increases the levels of stray light in the visible channels. The combination of these effects decreases the observed signal levels and the accuracy of the starsense measurements during local night.

The nominal lifetime for the GOES satellites is five years for the present series and seven years for GOES N-Q. Excessive degradation of the throughput of the visible channels could cause an increasing incidence of missed detections of high magnitude (low brightness) stars, particularly for the Imagers during local night. The consequence of these failures could be inability to obtain adequate attitude references, causing the image registration to degrade.

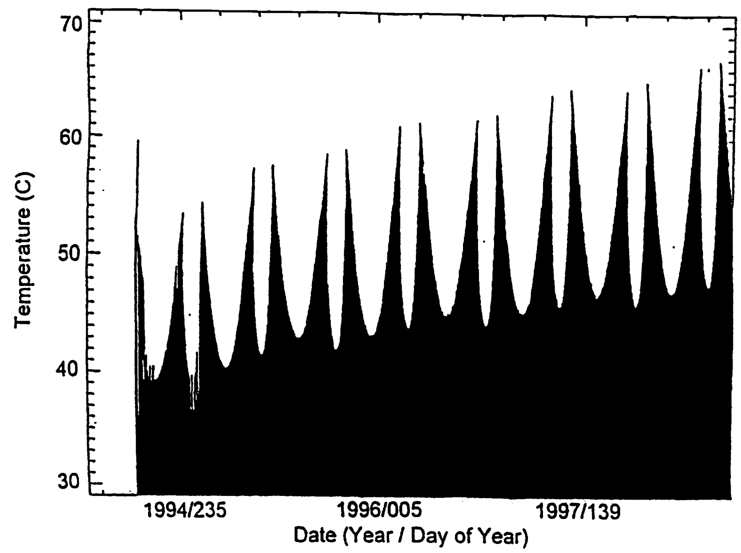

Figure 2. Maximum temperature of the GOES-8 Imager's scan mirror as a function of time.

The motors that drive the scan mirror on each sensor must also remain functional over the lifetime of the mission. As the reflective surface of a scan mirror absorbs more sunlight, the peak operating temperatures of the motors will also increase, and their probability of failure will increase as well. The GOES-9 satellite's operations now include pitch maneuvers to avoid overheating the motors. During four critical time intervals of approximately 20 days each per year, when solar heating is greatest, the z-axis of the spacecraft (nominal nadir) is pointed 4° east of nadir for several hours before local midnight and 4° west of nadir for several hours after local midnight. The scan mirrors of the Imager and the Sounder are constrained to point in directions that minimize heating, leading to a worst-case outage time of 6.5 hours. This constraint is applied in addition to the solar avoidance constraint that prohibits the Imager and Sounder from pointing within 6.25° and 8.5° of the sun, respectively, to avoid overheating their secondary mirrors.

4. COMPARISON OF STAR CALIBRATION WITH OTHER VISIBLE CALIBRATION METHODS

Stars have a number of features that make them good sources for radiometric calibration. They uniformly illuminate the full aperture of each sensor with collimated radiation. Each star in the GOES star catalog has a known color temperature, and most of these stars have spectral distributions that tend to match the reflective spectrum of the earth's albedo. As external sources, they provide an end-to-end calibration, reflecting and refracting from all of the same optical elements as light from the scene, but with no extraneous elements in the optical path. Most of the stars in the GOES star catalog are stable; variable stars have been cataloged, and have been excluded from this analysis.[6] Star measurements avoid the variability due to sun angle and viewing angle that are present in measurements of surface areas of the moon or of the earth.

The starsense measurements provide calibration data without decreasing the time available for earth observations. The GOES Imagers and Sounders perform starsense measurements on a regular, 30 minute basis throughout the lifetime of each sensor to determine attitude references. The time of each star detection, the star catalog number, and the observed signal level are archived in the GOES Processed Observation File. The identity of the detector within the array and the search window in which the detection occurred are recorded at the time, but are not retained in the archive. The archived signal levels can be analyzed statistically to determine long-term radiometric trends. The archived GOES 8 starsense measurements date back to April 25, 1995 (95/115); the GOES 9 measurements date to Aug 8, 1995 (95/220).

Although they are excellent sources for relative radiometric measurements, stars have a number of problems that make them less desirable as absolute radiometric standards for the Imager's Channel 1. Even the brightest stars observed by GOES correspond to effective albedo levels of <10% in an instantaneous-field-of-view (IFOV) of 28x28μradians. The electronic gain of the Imager's Channel 1 is increased by a factor of four during starsense measurements, to minimize A/D quantization errors. Also, Channel 1 responds to the radiance of extended targets when it views the earth, but it responds to the ensquared irradiance of a point source during starsense measurements. Conversion from irradiance to radiance requires an accurate knowledge of the IFOV of each detector and also the ensquared energy in each pixel.

The archived starsense signal levels are determined by summing the signal levels measured by the individual array elements. When the star straddles the two detection windows, it is detected in Channel 8 during the first window and in Channel 1 during the second window. Because of the half-pixel overlap between the two windows, the recorded signal value will exceed the value obtained from a detection of the same star in a single array element. The archives do not retain any information to indicate whether the star was detected in multiple array elements or in both windows. High energy charged particle striking the detectors or pre-amplifiers of the starsense channels can produce spurious signal and corrupt the starsense measurements. Because of these and other factors, there is considerable variance in measured signal levels of stars.

5. DIURNAL VARIATIONS IN IMAGE QUALITY

Stars are ideal point sources that can be used to measure the point spread function (PSF) of the visible channel. The images of stars tend to have full-width, half maximum (FWHM) values of less than 10 μrad during the daytime, but become severely de-focused during local night. For example, we compare starsense measurements of the two brightest stars taken by GOES 8 on July 9, 1997.

Figures 3 and 4 are plots of the signal level as a function of scan angle as the star α-Aql (Altair) drifted through the visible array of the GOES-8 Imager. The declination of α-Aql is $\delta = +8.73°$, so the long axis of the detector array was aligned in a northeast-to-southwest orientation. Figure 3 is the starsense measurement taken at 1737

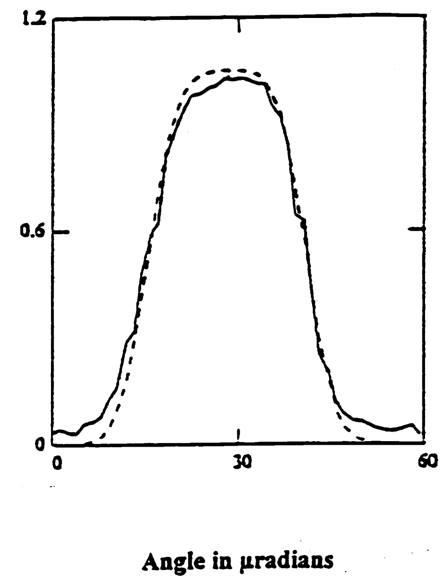

Figure 3. Intensity as a function of scan angle for α-Aql at 1237 local time (Detector V8)

________ Experimental data

------------ Gaussian blur circle

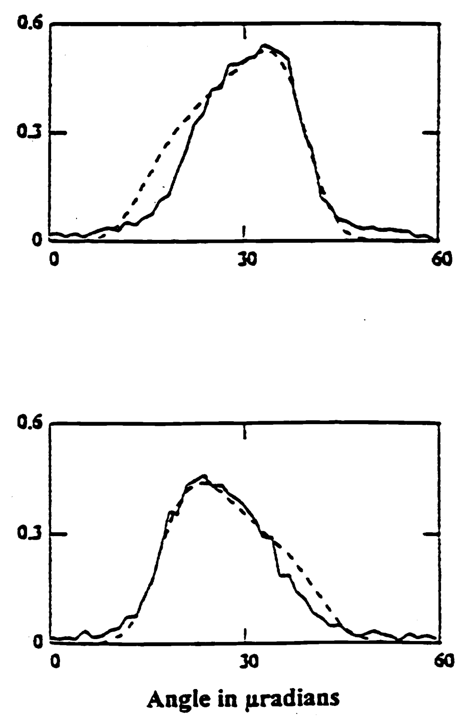

Figure 4a & 4b. Intensity as a function of scan angle for α-Aql at 1311 local time (Detectors V6 & V7)

__________ Experimental data

-------------- Gaussian blur circle

GMT (1237 local time). The star was only detected in array element V8, the southernmost element of the visible array, where it produced a symmetric image. Figures 4a and 4b show the same star, detected again at 1811 GMT (1311 local time), and straddling array elements V6 and V7. Because of image rotation, the star was observed first in array element V7, where its signal has a sharp rise and a gradual decay, then in array element V6, where its signal had a gradual rise and a sharp decay. The solid lines in Figures 3 and 4 are experimental data, the dashed lines correspond to a theoretical signal produced by a Gaussian blur circle with a FWHM of 8.5 μradians, traversing a detector with 26.5 μradian square IFOV's having a pitch of 28 μradians. This experimental data demonstrates that the acuity of the visible channels during local daytime is similar to that measured in ground tests.[7]

Figure 5 illustrates the two paths of the star through the visible array that can be inferred from the signals in Figures 3 and 4.

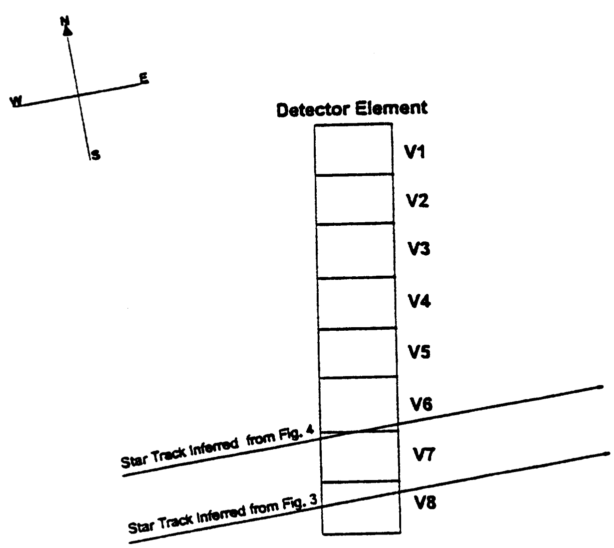

Figure 5. Star tracks produced by α-Aql inferred from Figures 3 and 4.

A starsense measurement of β-Ori (Rigel) taken at by the same sensor nine hours earlier on the same day, at 0237 GMT (2137 local time) produced a very different signal. The PSF was spread over four array elements: V4, V5, V6, and V7, spanning 112 μradians in the north/south direction. Figures 6 is a plot of the peak of the PSF as measured by array element V6, normalized to a value of 1.0 for a PSF in good focus centered on a single array element. The PSF is also spread out in the E/W direction, and intensity of the peak signal in a single detector is dramatically reduced.

The severe reduction in image quality illustrated in Figure 6 is typical of that produced by heating of the scan mirror during local night. In the winter, the image qualities of the two stars are reversed: β-Ori is in sharp focus during spacecraft day and α-Aql has a blurred image during spacecraft night. The GOES 8 Sounder's PSF degradation is similar to that of the GOES 8 Imager during local night. The deterioration of image quality during local night is less severe on the GOES 9 Imager and Sounder, due to their improved scan mirror design, but is still quite noticeable.

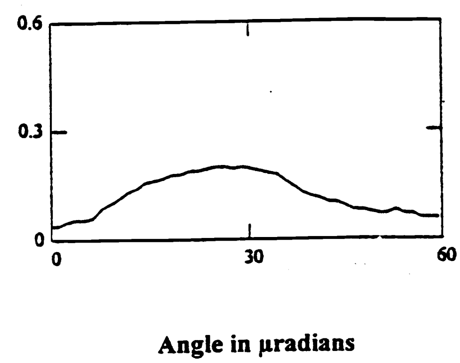

Figure 6. Intensity as a function of scan angle for β-Ori at 2137 local time (Detector V6)

6. CRITERIA FOR RADIOMETRIC ANALYSIS

When these raw measurements of signal levels of stars are processed by the starsense algorithm, they show a significant decrease during those times of the year when the star is observed near local midnight. Figure 7 is a plot of the measured signal levels from the GOES 8 Imager as a function of day of detection for β-Lib. The seasonal decrease in measured values that occurs during local night is obvious. To minimize the effect of nighttime image quality degradation, we have rejected starsense observations between 1900 and 0500 hours, local time (within 5 hours of local midnight.) Figure 8 is a plot of the same data as in Figure 7, the measured signal levels as a function of day of detection for β-Lib, but with the nighttime observations removed.

Discarding the nighttime observations produces annual gaps in the data from each star used for radiometric analysis. The time of year of the gap depends upon the right ascension of the star. The GOES star catalog excludes double stars and stars with large variations in intensity, such as α-Ori (Betelgeuse), but includes a number of stars with variability of up to about 10%. When selecting stars that are suitable for intensity measurements, we have deleted stars identified as variable.[6]

We have assumed an exponential decay model in which the logarithm of the intensity of the detections is plotted as a function of the day of detection. To obtain an accurate measure of the decay rate, we need a large number of star observations over a long interval of time. Therefore, we have only considered stars that have been observed a minimum of 600 times, with a minimum of 500 days between the first and last observation. We have also required a signal-to-noise ratio of at least 5.5 at the beginning of the time interval.

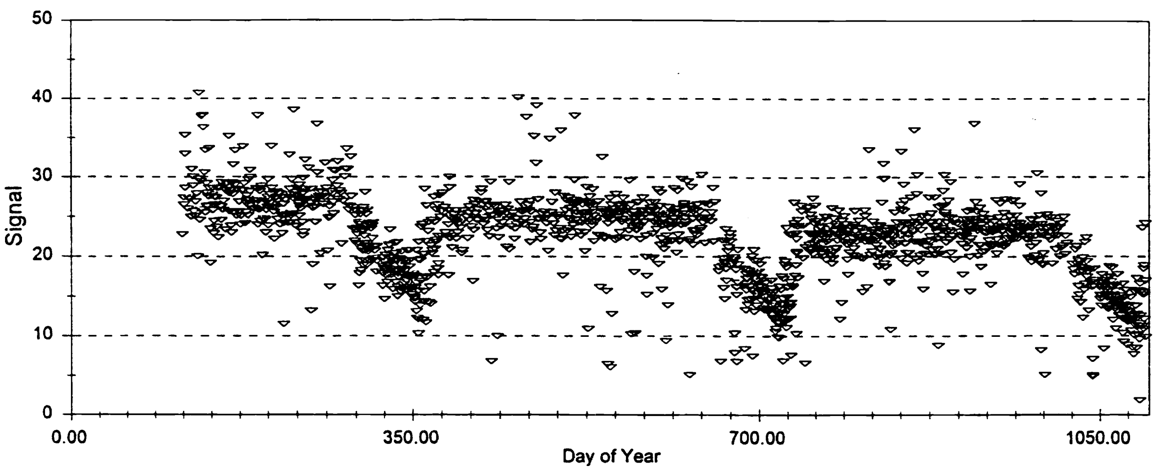

Figure 7. Signal levels of β-Lib measured by the GOES-8 Imager as a function of day of observation.

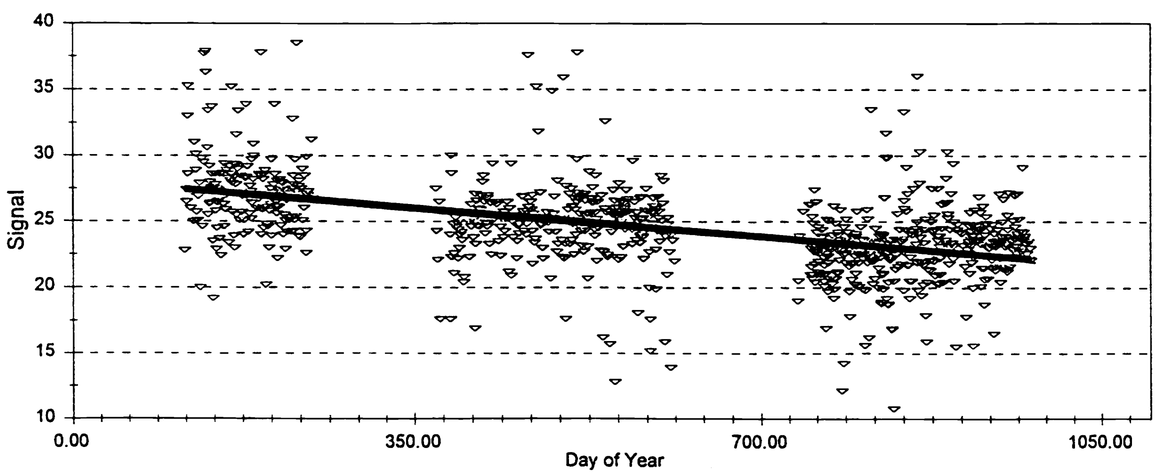

Figure 8. Signal level of β-Lib measured by the GOES-8 Imager as a function of day of observation with observations within 5 hours of local midnight deleted. (________ Exponential decay at 8.6%/year)

7. RESULTS OF RADIOMETRIC ANALYSIS

All four of the instruments exhibit statistically significant degradations. The GOES 9 Imager has a more rapid decline than the other three instruments, as well as a much larger standard deviation, when its starsense measurements are fitted to an exponential decay curve. The dominant reason for this decline appears to be an anomalous decrease in signal level during a period around the summer solstice of 1997. The average signal levels decreased sharply in late May and then appeared to recover by mid-August. This effect can be seen clearly in Figure 9, a plot of the measured signal levels for the star 40ϕ-2-Ori, with the detections within 5 hrs of local midnight deleted.

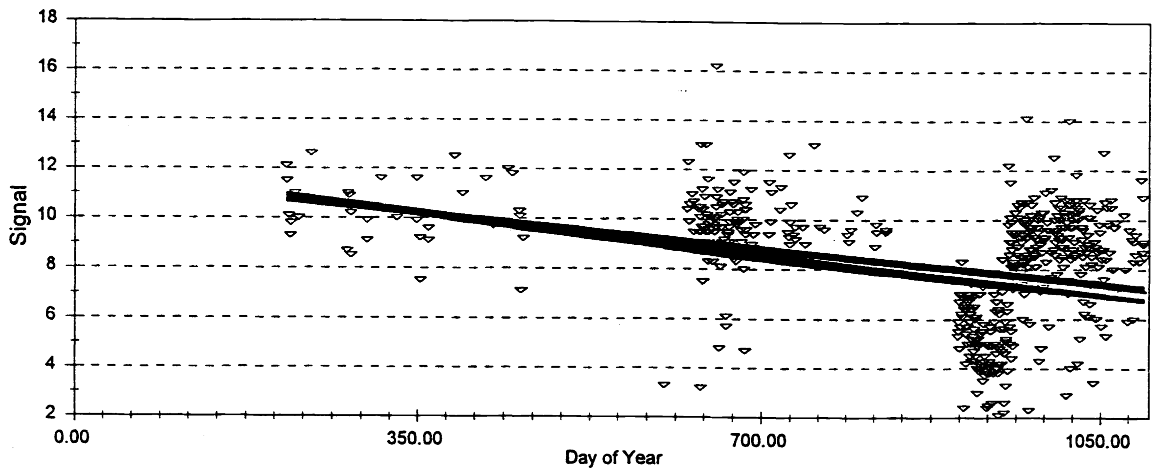

Figure 9. Signal level of 40 ϕ-2-Ori measured by the GOES-9 Imager as a function of day of observation with observations within 5 hours of local midnight deleted.

We have not been able to identify any cause for this behavior, either in the GOES 9 Imager's housekeeping data or in the starsense software. Because this behavior was anomalous, the GOES 9 Imager's degradation was analyzed both with and without the data from 97/150 to 97/230 (from May 30 to Aug 18, 1997). Figure 10 is a plot of the measured signal levels for the star 40ϕ-2-Ori, with the detections made within 5 hrs of local midnight deleted and detections made between May 30 and Aug. 18, 1997 also deleted.

The annual degradation rate of the GOES 9 Imager derived from the data with the anomalous interval included was 9.6%. When data from the anomalous interval was discarded, an annual degradation rate of only 4.9% was derived. The number of star signal trend measurements averaged in the analysis, the derived annual throughput degradation rate, and the standard deviation of that annual rate for each of the four sensors are presented Table 1. The GOES-9 Imager results are given both with the data from the anomalous interval both included and excluded.

8. CONCLUSIONS AND RECOMMENDATIONS

This analysis has demonstrated with a high level of statistical confidence that the throughput level of the visible channel on each of the four sensors has decreased during its operational lifetime. This effort is on-going; the addition of more recent data will lengthen the timeline and is expected to further improve the accuracy of the derived decay rates. It will be of special interest to see whether or not the GOES 9 Imager's anomalous throughput decline of the summer of 1997 re-occurs in the summer of 1998.

This study has shown that analysis of the starsense data over a multi-year baseline is a valuable technique for characterizing the long-term throughput degradation of the visible channels of the GOES Imagers and Sounders. Analysis of the diurnal

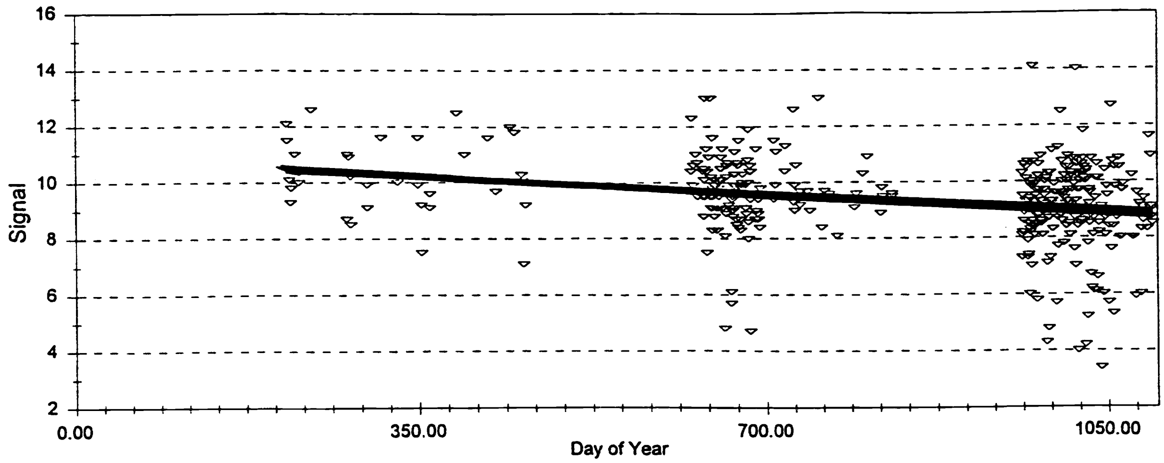

Figure 10. Signal level of 40 ϕ-2-Ori measured by the GOES-9 Imager as a function of day of observation with observations within 5 hours of local midnight and observations made between May 30 and Aug. 18, 1997 deleted.

Table 1. Annual throughput degradation rates of GOES 8&9 Imagers and Sounders

Sensor	**Number of stars**	**Annual throughput decrease**	**Standard deviation**
GOES 8 Imager	37	7.6 %	2.9 %
GOES 9 Imager (with anomaly)	34	9.6 %	5.5 %
GOES 9 Imager (without anomaly)	28	4.9%	2.4%
GOES 8 Sounder	40	6.9 %	2.4 %
GOES 9 Sounder	32	3.8 %	1.8 %

cycle in image quality also appears to be a promising diagnostic technique, particularly when the radiometric and image quality measurements are correlated with the measured temperatures of the scan, primary, and secondary mirrors. This technique, unlike many alternative visible calibration techniques, uses visible data that is already being collected, so it can be implemented on a routine basis without reducing the portion of the duty cycle that is available for earth observations. To improve the quality of this technique, it would be beneficial to retain the signal levels measured in the individual detector elements in the archived data.

9. ACKNOWLEDGMENTS

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